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Evaluation of Dam Decommissioning in an Ice-Affected River: Case Study

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COVER: Merrimack Village Dam, looking upstream, taken from Chamberlain Bridge (Photo courtesy of Gomez & Sullivan, Inc.)

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Abstract: Many dams across the United States are being decommissioned as a result of structural deficiencies or a desire to restore fish passage and to restore the natural stream. On northern rivers, dam removal affects the river ice processes and can result in increased ice jams and ice jam-related flooding. An analysis of the river system prior to dam removal is often necessary to ensure that increased ice jams, flooding, and damages do not result. This case study presents the types of analyses needed to investigate the ice impacts of the potential removal of the Merrimack Village Dam on the Souhegan River in Merrimack, New Hampshire. Of particular interest were the potential impacts to the historic Chamberlain Bridge. A HEC-RAS hydraulic model was used to estimate the ice jam thickness and resulting water surface profiles with and without an ice jam in place for both the pre- and post-dam-removal conditions. The results of this analysis indicate that removing the Merrimack Village Dam will not pose significant risk to the Chamberlain Bridge or to the area downstream.

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Preface

This report was prepared by Carrie M. Vuyovich, PE, Research Hydraulic Engineer, Remote Sensing/Geographic Information Systems (RS/GIS) and Water Resources Branch, and Dr. Kathleen D. White, PE, Research Engineer, Environmental Branch, US Army Engineer Research and Development Center (ERDC), Cold Regions Research and Engineering Laboratory (CRREL), Hanover, New Hampshire.

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This report was prepared under the general supervision of Timothy Pangburn, PE, Chief, RS/GIS and Water Resources Branch; Dr. Justin B. Berman, Chief, Research and Engineering Division, CRREL; and Dr. Robert E. Davis, Director, CRREL.

At the time this work was performed, Colonel Richard B. Jenkins was Commander and Executive Director of ERDC. Dr. James R. Houston was Director.

1 Introduction

More than 2.5 million dams were built in the United States over the past several hundred years to meet the power, water supply, flood control, and recreational needs of a variety of users (National Research Council 1992). These dams range in size from small farm pond dams less than six ft in height to the 770-ft-tall Oroville Dam completed in 1968.

Despite the large number of recently built dams, Doyle et al. (2003) noted that the period 1950–1970 could be termed the “golden age of dam building,” with tens of thousands of dams built each decade. The Federal Emergency Management Agency (FEMA) (2001) estimated that by 2020, 85% of large dams would be at or nearing their design lifespans. The American Society of Civil Engineers (ASCE) report card gave dams a grade of D in 2005, primarily due to increasing numbers of unsafe dams (ASCE 2005). The grade is based on the following observations:

- Between 1998 and 2005, the number of unsafe dams rose by 33%.
- Because of constrained budgets, the number of unsafe dams is increasing faster than those being repaired.
- The combination of rapid downstream development and inadequate past design practices, coupled with a predicted increase in extreme events, increases life safety risks.

ASCE (2005) notes that “On the federal side, federally owned and federally regulated hydropower dams are in good condition; however, continuing budget restrictions and increased attention to security are placing pressure on and limiting many agency dam safety programs.” The US Army Corps of Engineers (USACE) owns and operates 608 dams (USACE 2005a), of which 113 are concrete dams and the remaining are earthen embankments, rockfill, or timber crib dams. More than a quarter of these dams are more than 50 years old (Bowles et al. 1999). According to McGrath (2000), the Corps has 356 high-hazard, 36 significant-hazard, and 15 low-hazard embankment dams. Between 1990 and 2005, the National Performance of Dams Program (NPDP 2005) reported 15 Dam Incident Notifications for Corps dams, but no failures. The statistics are worse for the

thousands of non-Federal dams: during the two year period 2003–2005, the NPDP reported more than 67 incidents including 29 failures (ASCE 2005).

Increased awareness of the ecological, recreational, and economic issues, in addition to safety issues associated with dams, has led to reevaluation of their continuing usefulness (American Rivers et al. 1999, American Institute of Biological Sciences 2002, Heinz Center 2002). Interest in dam decommissioning, including dam removal, has grown substantially over the past 20 years. Decommissioning alternatives include dam removal, which is often assumed to be synonymous with decommissioning; the use of nature-like fishways to bypass a dam (e.g., the USACE's New Savannah Bluff Lock and Dam By-Pass); the use of rock arch ramps or boulder vanes (e.g., USACE projects on the Red River of the North at Fargo and Grand Forks); partial breaching (e.g., USACE projects on the Chattahoochee River); and dam reoperations, which the USACE is pursuing at several locations with The Nature Conservancy.

Most experts recommend a careful examination of potential impacts of dam removal (ASCE 1997, Heinz Center 2002, Conyngham et al. 2006), but the temptation exists to oversimplify the situation. For example, American Rivers (2002), summarizing work by Bednarek (2001), states "Though there are some negative ecological impacts associated with dam removal, Bednarek observes that most of these impacts have short-term effects on a river system." This attitude, combined with restoration costs ranging to more than three times the cost of removal (Born et al. 1998), can result in less-than-thorough alternatives analyses.

Dam decommissioning is a non-trivial issue that requires scientific, sociological, and economic analyses. The cumulative impacts of dam construction, human activities such as urbanization and deforestation, and natural events, can significantly disrupt the dynamic equilibrium of a river. Yet, watersheds do reach some new equilibrium state, which is then subject to further disturbance by dam decommissioning alternatives. The system changes resulting from decommissioning must be carefully studied to avoid unintended consequences, especially in the case of older dams.

Decision-making for dam decommissioning should address the degree of potential impact and recovery potential of the alternatives. Physical and economic constraints and public perceptions should be considered. Deci-

sion-makers should rely on appropriate quality and quantity data and analyses resulting in acceptable levels of risk and uncertainty. Non-traditional methods of cost allocation such as game theory have been used in evaluating decommissioning alternatives (Tanimoto 2003). The use of contingent valuation and multi-objective decision models should also be considered (see, e.g., Abdul-Mohsen 2005 and Kuby et al. 2005).

Conyngham et al. (2006) provide an overview of the ecological and engineering aspects of dam decommissioning, with an emphasis on dam removal. Of particular interest to the USACE as a major water resource manager is the potential for significant affects on the timing and peak values of flood hydrographs due to dam removal (ASCE 1997). Typical dam removal studies address open-water impacts of dam removal. However, as White and Moore (2002) point out, dam removals on northern rivers can also significantly affect the ice formation, growth, and breakup processes.

There are several examples of dam removals resulting in changed ice conditions that increased the frequency and severity of damaging floods (Tuthill and White 1997, White and Moore 2002, Vuyovich and White 2006, Tuthill et al. 2007). One important way dam removal can modify the river ice conditions is by allowing ice at breakup to travel farther downstream. Ice that was held upstream of the dam can reach locations downstream where ice jams have not occurred since the dam was built. As a result, development and infrastructure, such as bridges, downstream of the dam may be susceptible to ice damage. White (2001) suggested steps that can be taken to evaluate ice impacts over and above those suggested by ASCE (1997). This method was developed further by Vuyovich and White (2006) in an analysis of the effectiveness of an ice control structure. The current technical report presents a case study illustrating the analyses required to perform an evaluation of the impacts of dam decommissioning in an ice-affected river.

2 Case Study: Merrimack Village Dam

The Merrimack Village Dam is located at Merrimack, New Hampshire, on the Souhegan River approximately 2,000 feet upstream of the confluence with the Merrimack River. The present structure, an arched ogee spillway, has been in place since 1934. A dam has existed at the site since the early 1900s. The dam currently is not used for its intended purposes of hydropower or water storage, and recent inspections have uncovered deficiencies that need to be addressed. Removal of the Merrimack Village Dam would address the deficiencies and would provide the additional benefit of stream restoration (Gomez and Sullivan 2004).

Ice forms on the Souhegan River nearly every winter and is an important consideration in determining the impact of the removal of the Merrimack Village Dam on the Souhegan River ice conditions. Thus, the project makes an ideal case study, in which the objective is to investigate the impacts of the Merrimack Village Dam removal on the formation of potentially damaging ice jams downstream.

The case study follows the method presented by White (2001) and expanded upon by Vuyovich and White (2006). First, the historical ice jam reports and river geomorphology were analyzed to determine the most likely location for ice jams to occur once the dam is removed. In this case, it was assumed that ice will be able to pass farther downstream without the dam in place, though the bedrock formation beneath the dam is unknown. Based on that assumption, the most likely location for an ice jam to occur without the dam in place is at the upstream extent of the Merrimack River backwater, which extends approximately 1,000 feet upstream from the mouth of the Souhegan River. Of specific concern were ice impacts on the historic Chamberlain Bridge, located approximately 130 feet downstream of the Merrimack Village dam.

The ice conditions likely to be in place in the Souhegan River at the time of jam formation were then determined by reviewing historical meteorological and hydrological data to estimate ice thickness, ice jam volume, and a range of likely discharges during an ice jam event. Next, a HEC-RAS hydraulic model (USACE 2006) of the Souhegan River was used to estimate the ice jam thickness and resulting water surface profiles throughout the

Souhegan River. The HEC-RAS model was used to determine water surface profiles both with and without an ice jam in place to simulate pre- and post-dam-removal conditions. The HEC-RAS model was geo-referenced using GIS and GeoRAS (USACE 2005b) software to produce flood inundation maps of the pre-and post-dam removal ice jam scenarios in GIS. Finally, the ice jam results through the Chamberlain Bridge are reviewed in detail. Each of these steps is described in detail in the following sections.

3 Characterizing Ice Jams on the Souhegan River

The formation of breakup ice jams is strongly influenced by the winter weather conditions, the river discharge, and the river's geomorphology. The influence of the winter weather can be understood by examining the winter air temperatures. A strong relationship exists between the thickness of thermally grown ice and the number of accumulated freezing degree days that occur during the winter. Mechanical breakup occurs when there is sufficient flow to break up the solid ice cover and transport it downstream. Breakup jams often occur during warming periods that cause the ice cover to deteriorate to some degree, but warm temperatures without an increase in discharge generally lead to a thermal melt-out of the ice (USACE 2002). Ice jams occur at locations with limited ice conveyance, such as at sharp bends or channel constrictions, at bridges and other structures obstructing flow, or where the river slope decreases. All of these factors combined make predicting jams difficult without prior observations.

The Souhegan River is approximately 34 miles long with a drainage area of roughly 220 mi^2. The upstream portion of the river is relatively steep, and numerous dams have been built in this reach for hydropower and flood control (Gomez and Sullivan 2004). It is likely that the dams upstream reduce the amount of ice that travels to lower portions of the river. The McClane Dam, in Milford, New Hampshire, lies approximately at the midpoint of the river, below the Souhegan's steep upper half. Ice jams have been reported at the McClane Dam (IJDB 2007). Figure 1 shows the Souhegan River profile extending 30 miles upstream from the mouth.

Below the McClane Dam, at Milford, the Souhegan River flattens out significantly for 12 miles before reaching a series of rapids called Wildcat Falls in Merrimack, New Hampshire. Approximately one mile upstream of the rapids, the river forms a sharp oxbow, which is the location of several reported ice jams. A report (USACE 1980) on historical ice jams in Maine, New Hampshire, and Vermont conducted by the New England Division (now New England District) Corps of Engineers states that in nine of the 11 years between 1969 and 1980, a jam formed at this oxbow, sometimes causing minor flooding. According to the report, "The jam remains in

place until it melts, or until pressure from water and upstream ice force the jam to break up. Downstream of the ice jam, the Souhegan flows freely and once the jam breaks up, it moves downstream without further jamming." Without additional analysis it would be difficult to determine the release discharge from the oxbow. It is likely that a solid ice cover at the impoundment stops ice released from the oxbow without causing any damage, until the discharge is sufficient to carry the ice over the dam or the ice accumulation melts in place.

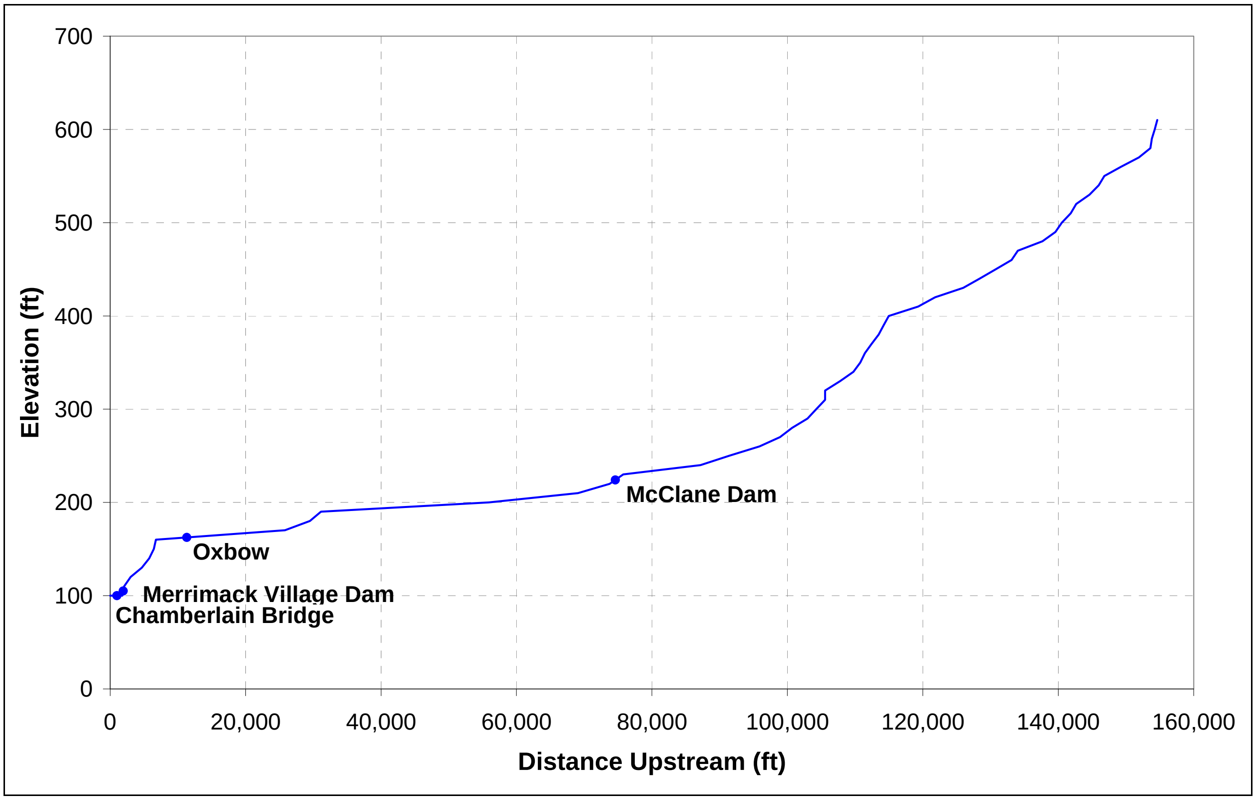

Figure 1. Souhegan River profile.

Frazil ice is produced in open water reaches with a steep gradient during periods of sub-freezing temperatures. Once frazil ice encounters a slow-moving reach of the river, it tends to accumulate against and beneath thermally grown ice, thickening and strengthening the ice cover. It is likely that significant amounts of frazil ice are produced in the section of rapids between the oxbow and the impoundment. Frazil ice that currently deposits beneath the ice cover at the impoundment is likely to travel farther downstream once the dam is removed.

A sediment island in the Souhegan River marks the upstream extent of the Merrimack River backwater (Fig. 2). This island is located approximately

1,000 feet upstream of the confluence with the Merrimack River and 800 feet downstream from the dam. Typically, sediment settles out when fast-moving river reaches a slow-moving section, such as the backwater of a larger river at a confluence. Frazil ice settles out under similar conditions, accumulating on the underside of an ice cover rather than in the channel bed. Once the dam is removed, frazil ice generated in the Wildcat Falls reach likely will pass through the Chamberlain Bridge and deposit near the sediment island, creating a solid, strong ice cover. This island represents the most likely locations for ice jams to occur once the dam is removed. A site map is shown in Figure 3.

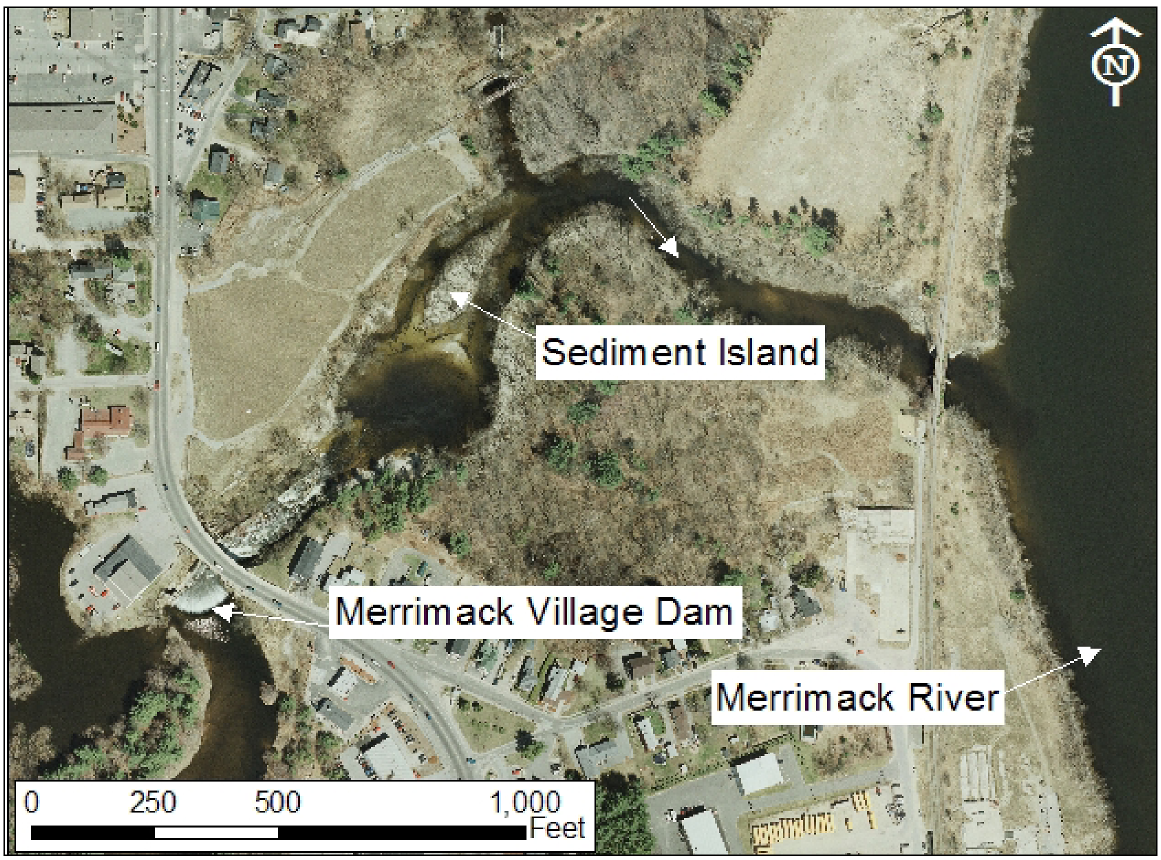

Figure 2. Lower Souhegan River and sediment deposits. (Photo courtesy of Gomez and Sullivan.)

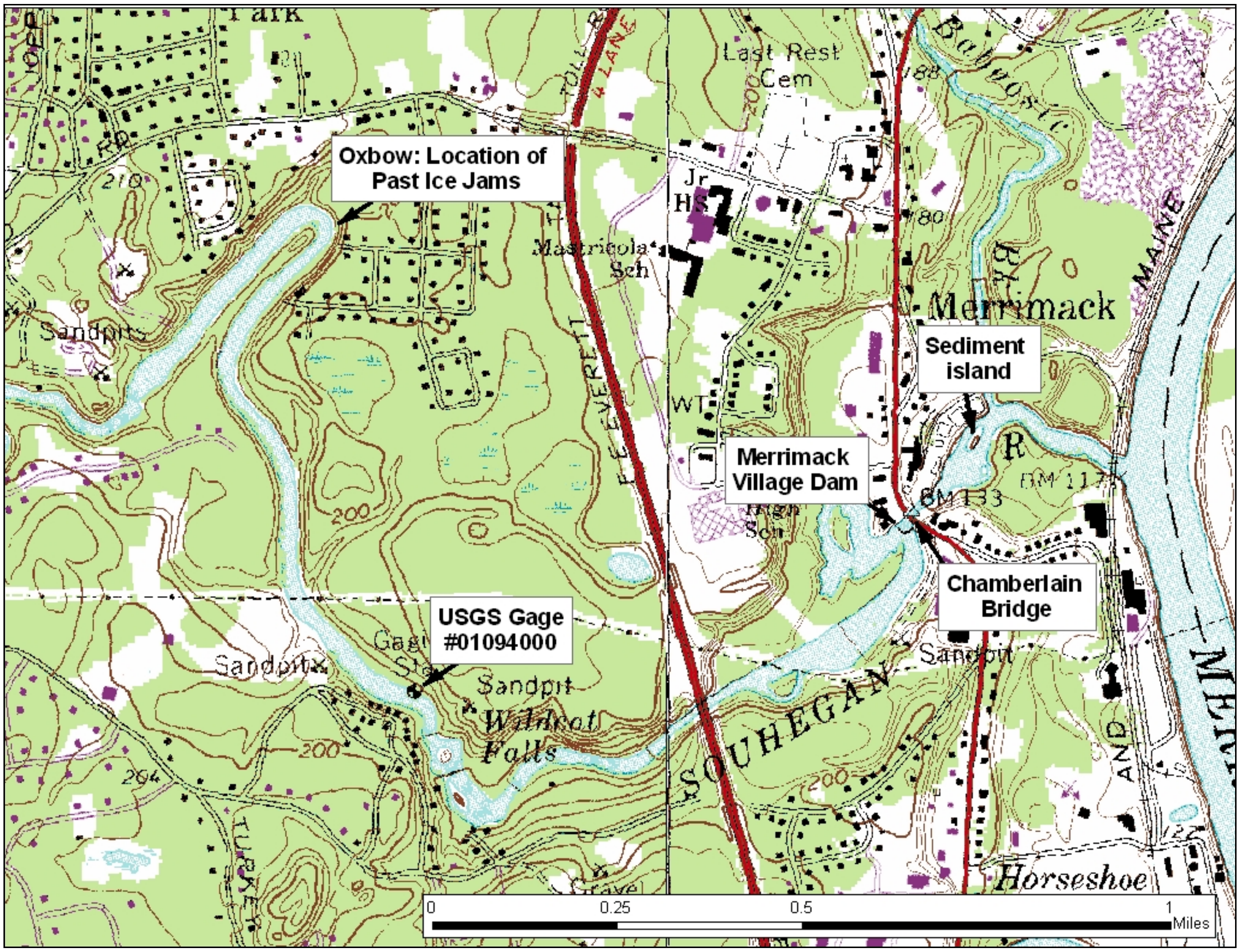

Figure 3. Site map. (Source: USGS topographical map, Nashua North, New Hampshire.)

4 Analysis of Historical Data

Standard investigations of river ice jam occurrence (Tuthill et al. 2003, Vuyovich et al. 2005) include an extensive review of recorded ice events and analysis of meteorological and hydrological data at relevant stations. Historic ice jam events were reviewed for information on where jams occur, resulting stage increases, damages, and relevant conditions at the time of the event. Meteorological data were used to estimate ice thickness and ice volume contributing to the ice jam. Hydrological data were used to determine the range of discharges at which an ice jam could exist. This information is used to develop the input parameters for the HEC-RAS model.

Historical Ice Events

This study included a limited review of historical ice events using the CRREL Ice Jam Database and the New England District of the Army Corps of Engineers' online library of documents. A more comprehensive search of newspaper and town archives possibly could have uncovered additional events or details, but was beyond the scope of the current effort. This review revealed an active ice regime on the Souhegan River.

There are three recorded ice jams on the Souhegan River in Merrimack in the Ice Jam Database (IJDB 2007). The 1977 event came from a report by the New England Division (now New England District), US Army Corps of Engineers (USACE 1980). According to the report, nine ice jams occurred between 1970 and 1980, with the jam of March 1977 being the worst. According to an interview with local officials, "The jam [occurred] at one of the oxbows in the Souhegan River, approximately 8,000 feet upstream of the F.E. Everett Turnpike Bridge." The two other jams (1964 and 1968) were reported at the USGS Souhegan River gage at Merrimack. These reports typically do not give specific details regarding location or damages. It is likely that these jams also occurred at the oxbow, which is located approximately 4,000 feet upstream of the gage.

Based on the frequency of jams reported in the USACE report, it is reasonable to assume that additional ice jams have occurred that did not cause serious damages and therefore were not reported. Often historical ice event data are not readily available or reported. One reason for the under-

reporting of ice events involves *perception stage* (Gerard and Karpuk 1979), which is defined as the minimum stage at which a source will perceive an event. If an ice jam occurs, but does not exceed the perception stage, most observers do not report the event. Table 1 summarizes the historical record of ice jams, along with temperature and discharge data associated with the events.

Table 1. Summary of recorded Souhegan River ice jam events.

Date	Description/location	Time to peak (days)	Average daily discharge (cfs)	AFDD (°F-days)	Estimated ice thickness (in.)
10 March 1964	Ice jam reported at gage	3	1,100	834	14.4
19 March 1968	Ice jam reported at gage	3	3,800	994.5	15.8
March 1977	oxbow 8000' u/s of Everett Turnpike Bridge	No data available	No data available	985	15.7
9 jams between 1969 and 1980	oxbow 8000' u/s of Everett Turnpike Bridge		1,800–3,200*	805.9†	14.2**

* Based on maximum winter discharge for years of available data (1969–1976)
† Average maximum annual AFDD 1969–1980
** Ice thickness based on average AFDD

Meteorological Data

Air temperature data are used to estimate ice thickness as well as to analyze historical ice events. Ice thickness is a necessary input parameter to HEC-RAS for modeling an ice cover or ice jam event. Ice thickness was also used to estimate the ice volume contributing to an ice jam.

Daily maximum and minimum air temperature data were retrieved from National Weather Surface (NWS) meteorological stations. The NWS station #275712 in Nashua, New Hampshire, with a period of record from 1885 through the present, was the primary source of temperature data.

Estimation of Ice Thickness

Ice growth on a water surface is a function of heat transfer at the ice/water interface. Temperature data were used to estimate ice thickness on the Souhegan River based on accumulated freezing degree days (AFDD) (White 2004). In this method, thermally induced (but not frazil) ice thickness can be estimated on a given date during the winter using temperature

data in the previous months. Freezing degree-days (*FDD*) represent the difference between the average daily air temperature (T_a) and 0°F, where a difference in temperature below freezing is positive and above freezing is negative. Accumulation of FDD begins in the fall when temperatures drop below freezing and continues throughout the winter. The peak annual net AFDD is a good indicator of winter severity. AFDD can provide an estimate of ice thickness (t_{ice}) in inches on a particular day using the modified Stefan equation presented in USACE (2002):

$$t_{ice} = C\sqrt{AFDD} \tag{1}$$

where C is a coefficient, usually ranging between 0.3 and 0.6, and AFDD is in °F-days. A coefficient of 0.5 was used to calculate ice thickness in Merrimack based on suggested values for the river type (USACE 2002). In general, the ice thickness used in the HEC-RAS ice routine does not greatly affect the results as long as the value used is within a reasonable range.

Although this method provides a reasonable estimate of ice growth caused by thermal processes, it is important to note that the ice thickness may be underestimated because of other factors, such as water velocity and the presence of a snow cover on top of the ice. Also, frazil ice deposition can contribute to ice thickness. Figure 4 shows the estimated maximum ice thickness caused by thermal growth for each year of record. Based on the AFDD analysis, the average maximum annual ice thickness on the Souhegan River is 13.4 inches (1.12 ft).

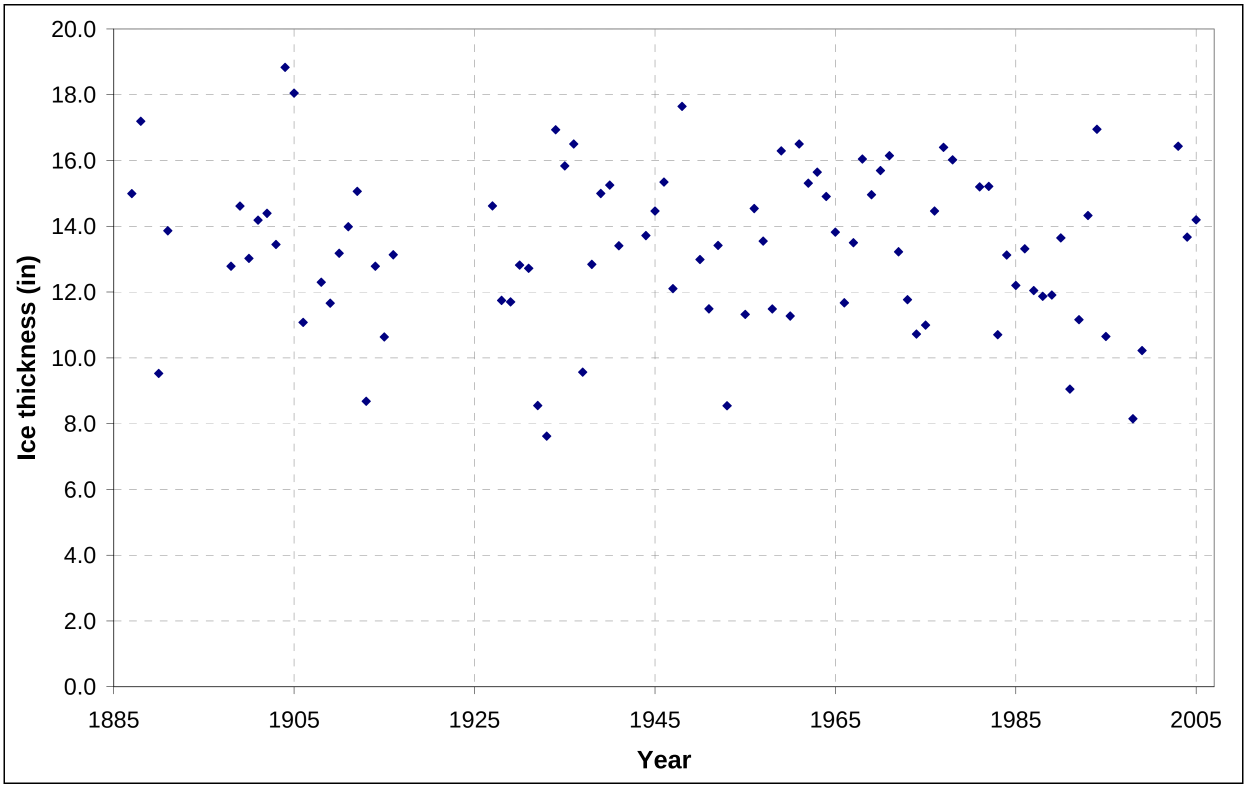

Figure 4. Estimated ice thickness for each year using Nashua, New Hampshire, temperature data.

Estimation of Ice Volume

The volume of ice that contributes to an ice jam determines the thickness and length of the jam. Calculating ice volume involves the following steps: 1) estimate surface area of ice and multiply by average ice thickness to get total volume; 2) determine ice transport losses based on channel morphology and historical records, if any; 3) decrease total ice volume by transport losses to determine ice volume available to jam.

In this case study, the contributing reach extends 14 miles upstream to the McClane Dam in Milford, New Hampshire. Surface area was estimated using a USGS topographic map of the area. Ice thickness was calculated using the AFDD method described above. The ice volume is reduced during transport, either stranded in the overbanks or eroded as a result of friction. The percentage of the ice volume lost depends largely on the characteristics of the specific reach. Earlier estimates ranged from 20% to 80% (Lever et al. 2000). Losses of 50% were used for this relatively small reach because the discharge is largely contained within the channel at breakup flows. Some ice is expected to be lost during a jam at the oxbow, and in fast-moving sections or rapids it is unlikely that a solid ice cover ever

forms. The total volume of ice estimated to contribute to a jam in the lower Souhegan River is 3,500,000 ft^3. A sensitivity analysis showed that, within a reasonable range, using a lower or higher volume of ice in the model will impact only the upstream extent and thickness of the ice jam. The ice jam formation through the Chamberlain Bridge and up to the current location of the Merrimack Village Dam will not be impacted.

Hydrological Data

Discharge data are used to analyze historical ice events and develop a range of discharges at which an ice event is likely to occur. The discharge range at which an ice jam can form and release depends on the ice thickness and ice strength. Sufficient flow is required to break up a solid ice cover and transport it downstream. A gradual rise in flow over many days or weeks often will weaken and melt the ice cover in place, thereby avoiding a dynamic breakup. Significant events generally result from a rapid rise in discharge that breaks up a strong ice cover and transports the ice downstream to a point where the downstream forces are not enough to convey the ice through and it jams. At some greater discharge the ice jam may release when it can no longer withstand the downstream forces. Figure 5 illustrates the process from competent ice cover to breakup to jamming, followed by jam failure.

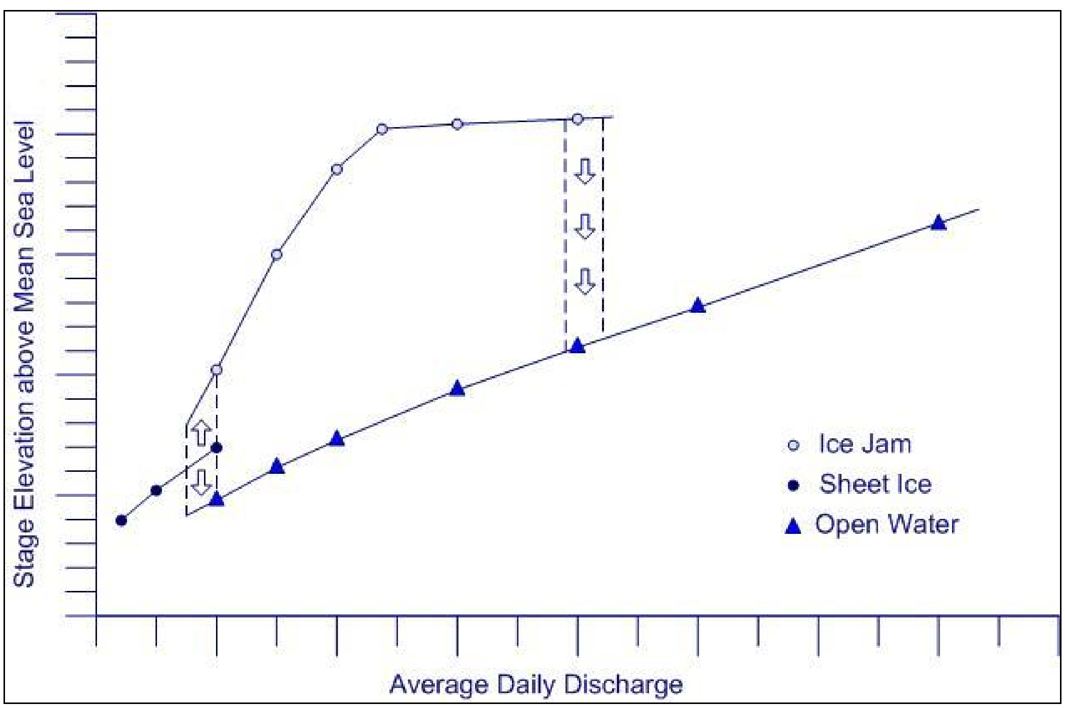

Figure 5. Example of ice-affected stage-discharge curve. (After Tuthill et al. 1996.)

Average daily river discharge data were obtained from USGS Gage #01094000 (USGS 2007a), which is located on the Souhegan River at Merrimack, New Hampshire, approximately one mile upstream from the dam, and has a drainage area of 171 square miles. This gage has a period of record dating from 1907 through the present, though a gap in the data exists between 1976 and 2001. The Merrimack River gage at Goffs Falls (USGS gage #01092000; USGS 2007b) was used to observe the pattern of increasing and decreasing discharge when Souhegan River data were unavailable.

The maximum discharge an ice jam can withstand before failure typically results in the highest stages and represents the worst-case scenario. The maximum discharge reached during a recorded ice event was 3,800 cfs in 1968. Between 1969 and 1976, nine ice jams were reported, but exact dates are not known. The maximum discharge during those winters, when Souhegan River discharge data are available, ranged between 1,800 and 3,200 cfs. The maximum ice jam discharge on the Souhegan River may be greater than the discharge available for known jams, but it is unlikely that a significantly larger event occurred that was not recorded.

5 Ice Hydraulic Model

The USACE Hydrologic Engineering Center's River Analysis System (HEC-RAS) is used to perform one-dimensional analysis of a river system (USACE 2006). The additional capability to model wide-river ice jams (Daly et al. 1998, Tuthill et al. 1998) makes it a useful tool for evaluating the impacts of a channel modification project on rivers with an active ice regime. A calibrated open-water HEC-RAS model developed for this reach of the Souhegan River by Gomez and Sullivan (2004) was geo-referenced and modified to simulate ice conditions. The reach was modeled with and without the dam in place in both open-water and ice-affected conditions.

A number of material properties of ice need to be input to HEC-RAS to model an ice jam (e.g., White 1999). Table 2 lists the property values used in this study. Default values supplied in HEC-RAS for the specific gravity of ice, the angle of internal friction, the porosity of the ice accumulation, and the ratio of lateral to longitudinal ice stresses were considered reasonable for this application. Estimates for other parameters that required additional analysis are described below.

Table 2. Summary of HEC-RAS ice properties used in model.

HEC-RAS ice properties	Value used in model
Specific Gravity of Ice	0.916
Angle of Internal Friction	45°
Porosity of Ice Accumulation	0.4
Ratio of Lateral to Longitudinal Ice Stresses	0.33
Manning's n value	0.7*
Maximum Under-Ice Velocity	15 fps†

~~1~~*Allowed to change based on ice thickness within ice jam extent.
† Within ice jam extent. Default value (5 fps) used in all other areas.

Geo-referencing

This model was geo-referenced to provide an effective way of displaying the results of the ice-affected runs (Fig. 6). The geo-referenced cross sections were merged with the existing cross sections so that the original geometry remained the same. The open water models of both pre- and

post-dam removal conditions were simulated and compared to the original results. The geo-referenced water surface profiles matched the original profiles to within 0.01 ft at every cross section. Figure 7 shows the geo-referenced profile results for the open water pre-dam removal test compared to the original results.

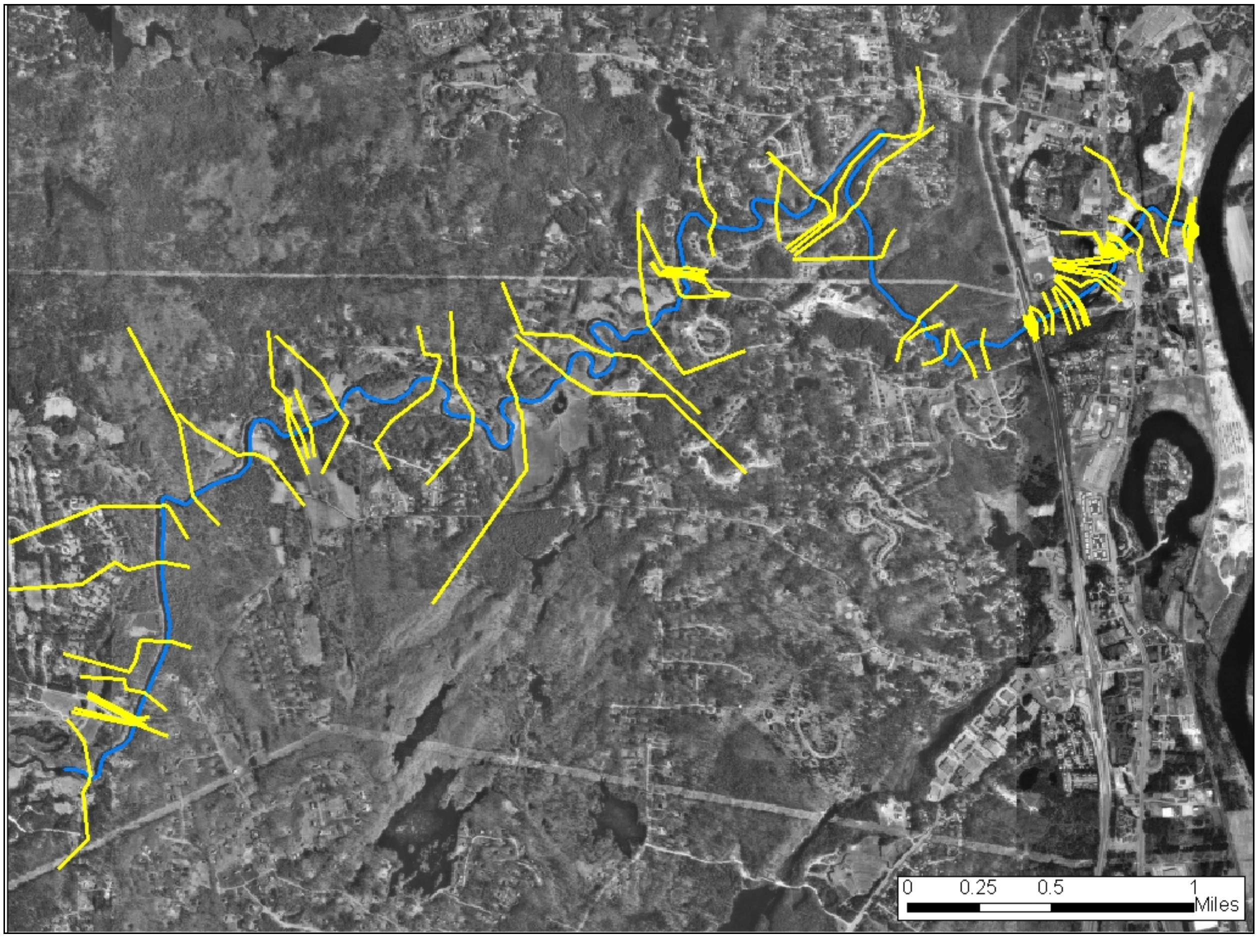

Figure 6. Geo-referenced HEC-RAS model of the lower Souhegan River.

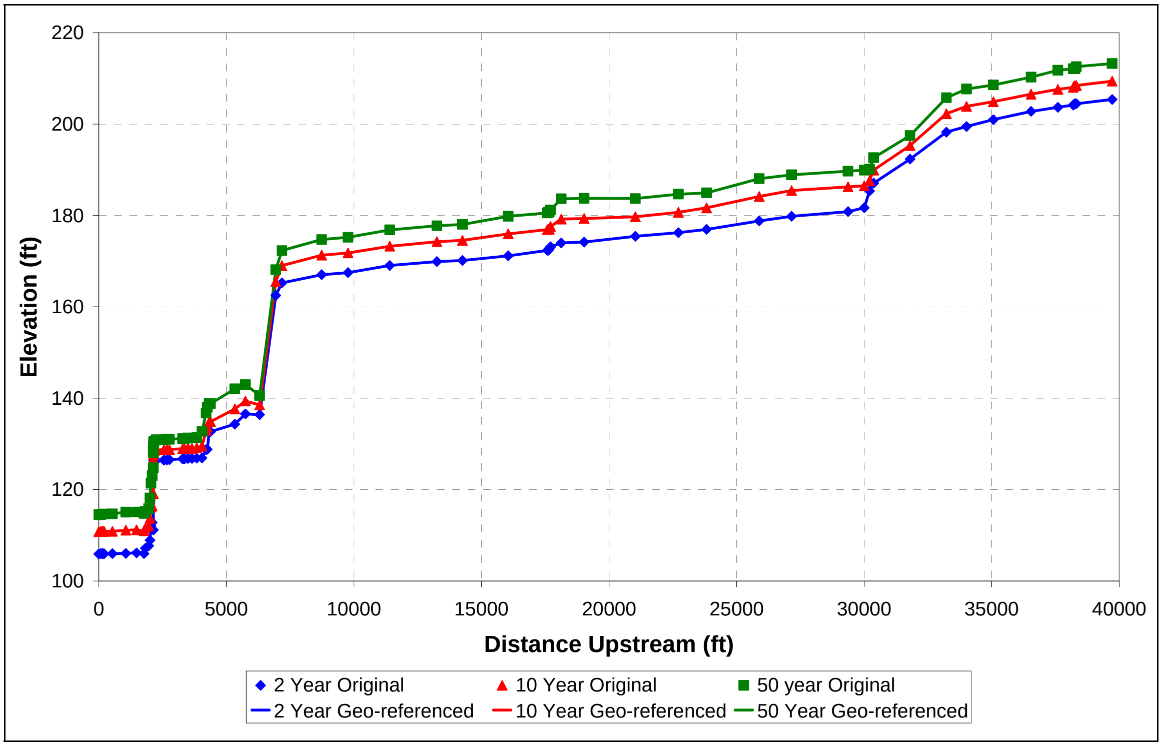

Figure 7. Open-water profile for original and geo-referenced HEC-RAS models.

Manning's n Value

The initial Manning's n value used for the roughness of the ice cover was 0.07, which was the recommended default value in HEC-RAS and a reasonable value for this application (White and Daly 1997). Within the ice jam reach, the option to vary the Manning's n value based on the thickness of the jam was selected in HEC-RAS.

Maximum Under-Ice Velocity

The maximum under-ice velocity parameter used in HEC-RAS is a useful modeling tool that prevents the ice jam from thickening to the bed and blocking the entire channel with ice (USACE 2006). HEC-RAS estimates the thickness of a floating wide river jam by solving the ice jam force balance equation. If the calculated flow velocity under the jam reaches the value of the maximum under-ice velocity set by the user, the ice jam thickness is not allowed to increase further during the solution procedure. In this case, the ice jam force balance equation cannot be solved and the estimated jam thickness may be suspect. If the maximum under-ice velocity is reached along significant lengths of the ice jam, the value of the maximum under-ice velocity parameter may be increased, but there should be some physical justification for doing this.

The concept of a maximum under-ice velocity has been used in a number of numerical and physical model studies of ice jams (Tuthill et al. 1998, Healy et al. 1997, Flato and Gerard 1986). There is a physical basis for a maximum under-ice velocity based on erosion of ice pieces from the underside of a floating jam with full-width water flow beneath. For this type of classic wide river jam, scaled erosion velocities ranging from 3.3 to 6.6 ft/s (1.0 to 2.0 m/s) have been measured in physical models (Tuthill and Gooch 1998) and in the field by Beltaos and Moody (1986). The concept of an under-ice erosion velocity assumes a floating ice jam with a relatively uniform under-ice flow depth and uniform water velocity across the channel.

If an ice jam is partially grounded, or the ice accumulation is mechanically locked in place by channel obstructions, under-ice erosion velocities higher than cited in the literature may be possible. For example, an ice jam may form in a steep reach upstream of the intact sheet ice on a dam impoundment. As the discharge continues to rise, water velocities in portions of the channel may exceed the commonly accepted non-eroding maximum of about 6 ft/s. In these higher flow areas, ice pieces may erode away, developing preferential high velocity flow paths beneath the jam, while the bulk of the ice accumulation remains stable and mechanically locked in place. Tuthill (in prep) observed this process in a physical model study of a pier-type ice control structure, and measured flow velocities that were much higher than the commonly accepted 4- to 6-ft/s upper threshold for non-erosion of ice pieces. Another example is an ice jam that commonly forms on a steep section of the Mad River above a small reservoir near Moretown, Vermont. In this rapids section, high velocity flow erodes a channel beneath and through the jam, but because the ice accumulation has nowhere to go, the jam remains in place throughout the bulk of the breakup period.

On the Souhegan River, an ice jam located in the Merrimack River backwater would be restricted by the downstream ice cover, the channel banks, and the Chamberlain Bridge abutments as it extends upstream. Velocities immediately upstream of the bridge can range from 10 to 15 ft/s during open water flow. If the maximum under-ice velocity parameter is set too low within this reach, the thickness of the jam will be artificially reduced. For this study, the maximum under-ice velocity was set to 15 ft/s within the ice jam extent to allow the ice jam to progress up the steep section from the Merrimack backwater past the Chamberlain Bridge.

Simulations

For this analysis, the two-year and the ten-year open water flood flows, based on the Federal Emergency Management Agency's Flood Insurance Study for the Town of Merrimack, were used to model the range of maximum ice jam discharges (FEMA 1979). At the location of the ice jam, the two-year discharge is 3,200 cfs and the ten-year discharge is 8,370 cfs. Based on the review of hydrologic data and historical ice events, the actual maximum discharge an ice jam could withstand on the Souhegan River is estimated to be between these two discharges.

To model the existing conditions, the toe of the jam was located at the upstream end of the impoundment behind the dam where the ice is likely to encounter a solid ice cover. To model the conditions once the dam is removed, the toe of the jam was located at the downstream end of the sediment island where the ice is likely to encounter a solid ice cover in the backwater of the Merrimack River. Table 3 gives a summary of each model run.

Table 3. Summary of HEC-RAS simulations.

Run	Location of jam toe	Discharge (cfs)	Ice jam extent upstream (ft)	Total volume (ft^3)
Existing conditions	Upstream end of impoundment	3,140	3,487	3,528,095
Existing conditions	Upstream end of impoundment	8,370	1,483	3,650,594
Dam removed	Sediment island, 1000 ft u/s of Merrimack River	3,140	3,144	3,657,230
Dam removed	Sediment island, 1000 ft u/s of Merrimack River	8,370	2,593	3,654,522

6 Results

The following results were observed from the HEC-RAS simulations without the Merrimack Village Dam in place:

- Once the dam is removed, an ice jam occurring downstream would extend upstream through the Chamberlain Bridge.
- The ice jam surface level, which is 4.5 ft from bridge superstructure, is approximately the same for the two-year and ten-year recurrence interval discharges.
- An ice jam event occurring during the two-year discharge would result in an ice and water surface elevation of approximately 122.0 ft, 11 ft higher through the bridge than during a two-year open water event, elevation 111.0 ft.
- An ice jam event occurring during the ten year discharge would result in an ice and water surface elevation of approximately 122.25 ft, 8.5 ft higher through the bridge than during a ten-year open water event, elevation 113.75 ft.
- Ice jams occurring after the dam was removed did not result in significantly more flow out of banks than the open water events.
- Velocities beneath the ice jams were under 8 ft/s in all areas except immediately upstream of the bridge, where they reached 9.5 ft/s during the two-year flow and 18 ft/s during the ten-year flow.

Figures 8–11 show the HEC-RAS simulation results of the two-year and the ten-year discharges with an ice jam for the dam in place and removed. The open water profile is also shown.

The geo-referenced results were imported into GIS to map the flood inundation with and without the dam in place. Since the original cross sections were used in place of the cross sections cut from the digital elevation map, the flood inundation does not cover all areas of the river, but it can be used for comparison to look at the pre- and post-dam removal conditions. The

ice jams shown on the maps were digitized by hand to show where the ice jam was modeled in HEC-RAS. Later versions of GeoRAS will allow the user to import the ice jam as well. Figures 12–15 show the inundated areas due to ice jams at the two-year and ten-year discharges with and without the dam. The open water two-year and ten-year flood inundated areas are also shown.

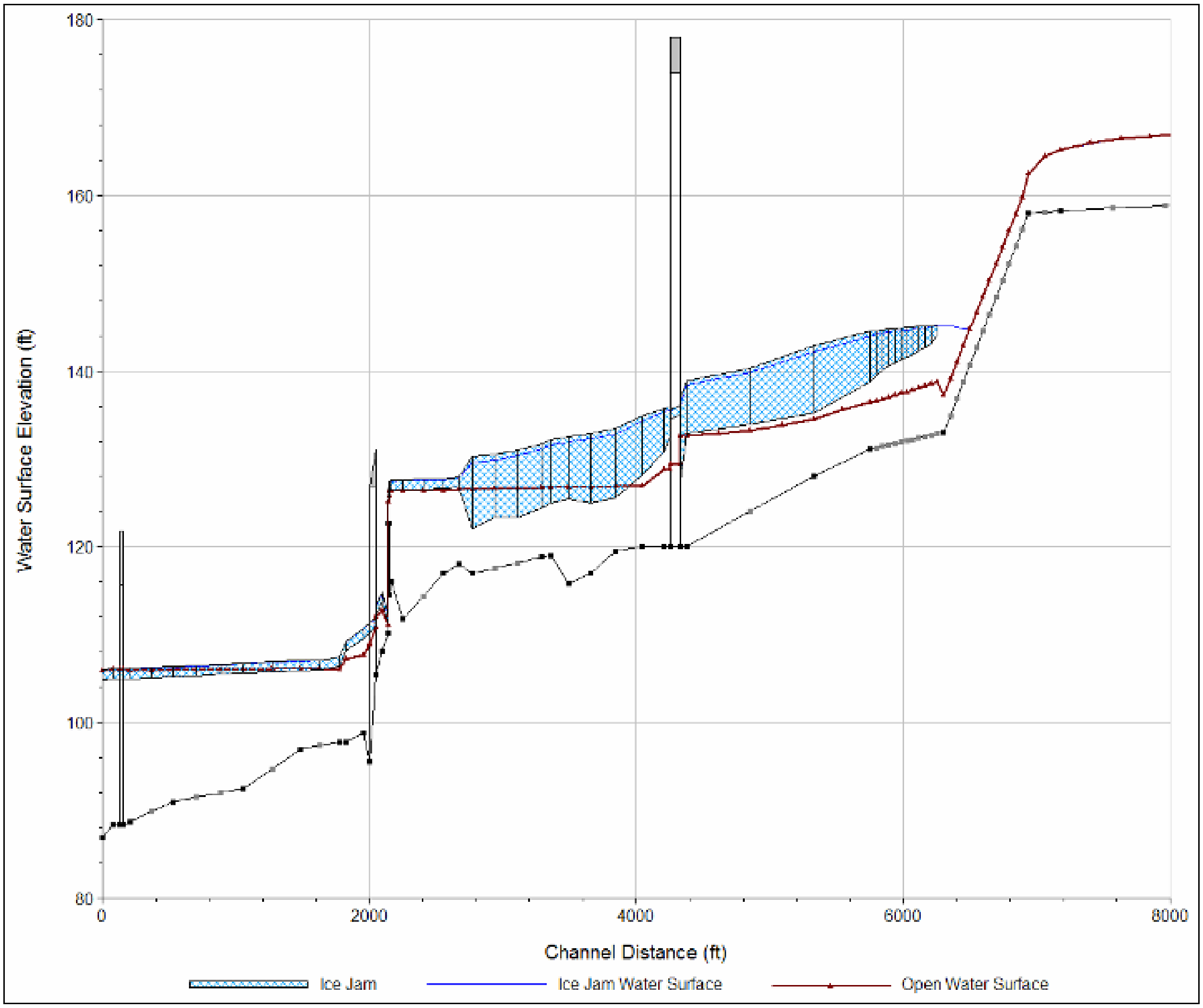

Figure 8. HEC-RAS ice jam and open water profiles, with dam in place for the two-year discharge.

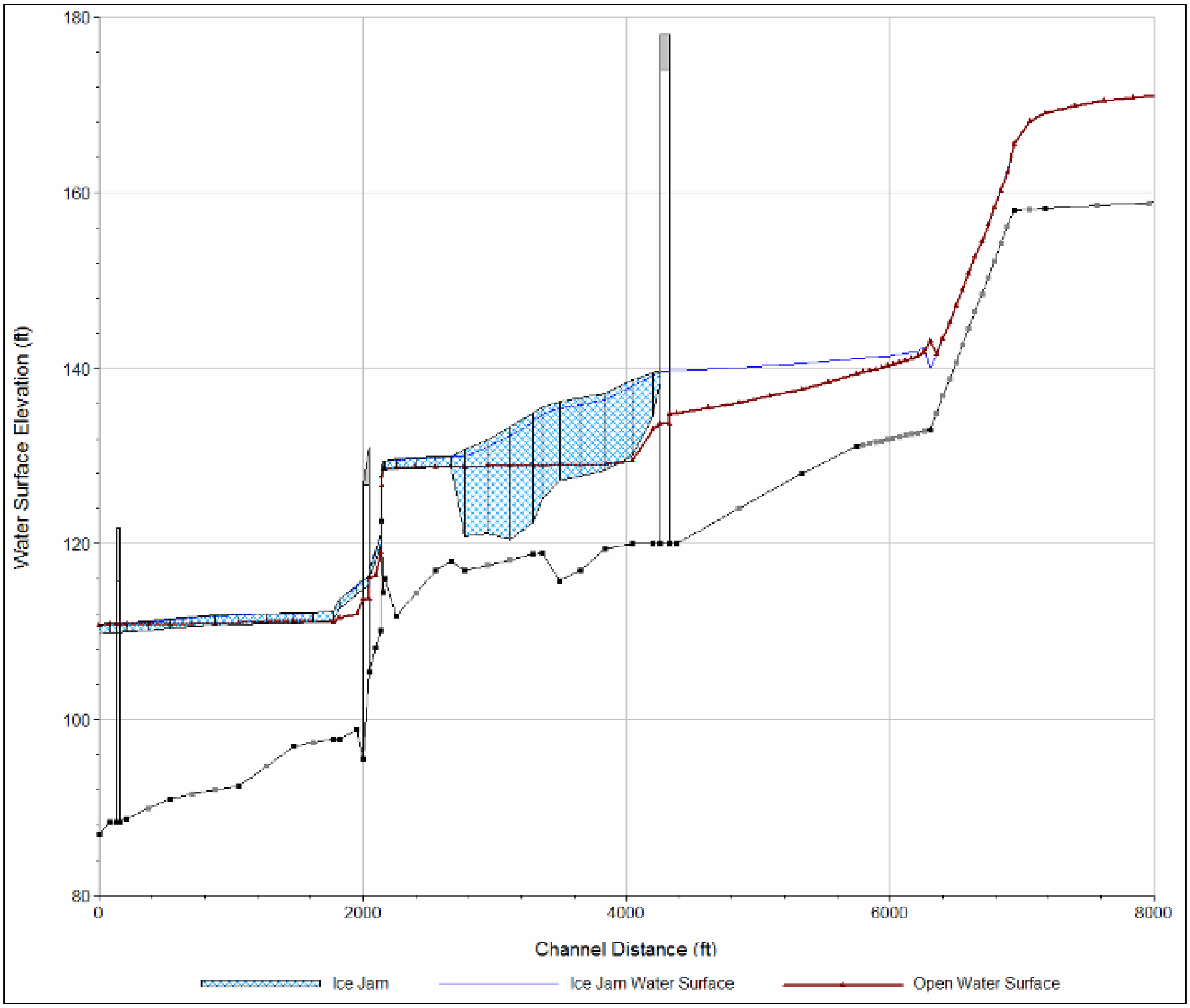

Figure 9. HEC-RAS ice jam and open water profiles, with dam in place for the ten-year discharge.

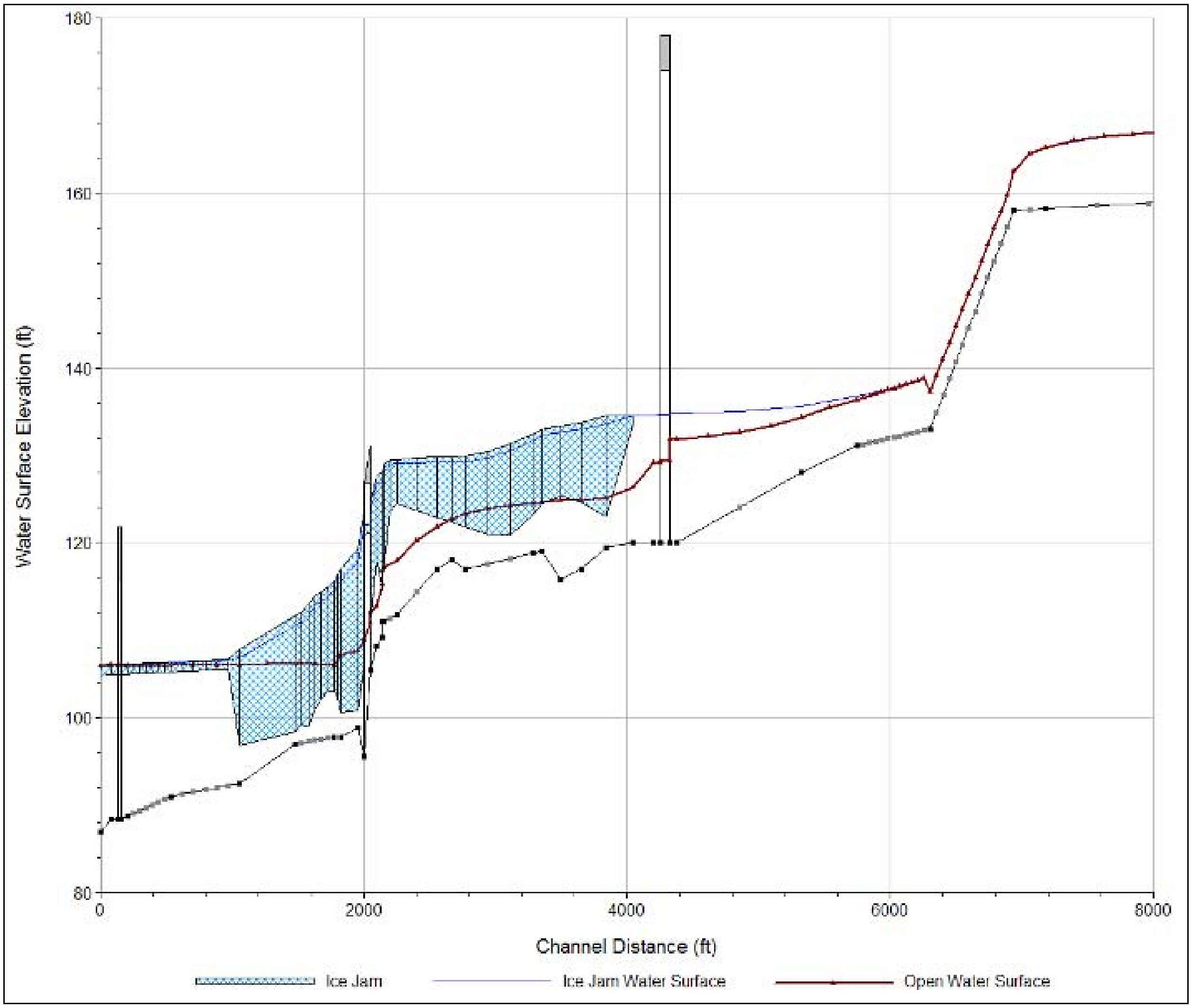

Figure 10. HEC-RAS ice jam and open water profiles, with dam removed for the two-year discharge.

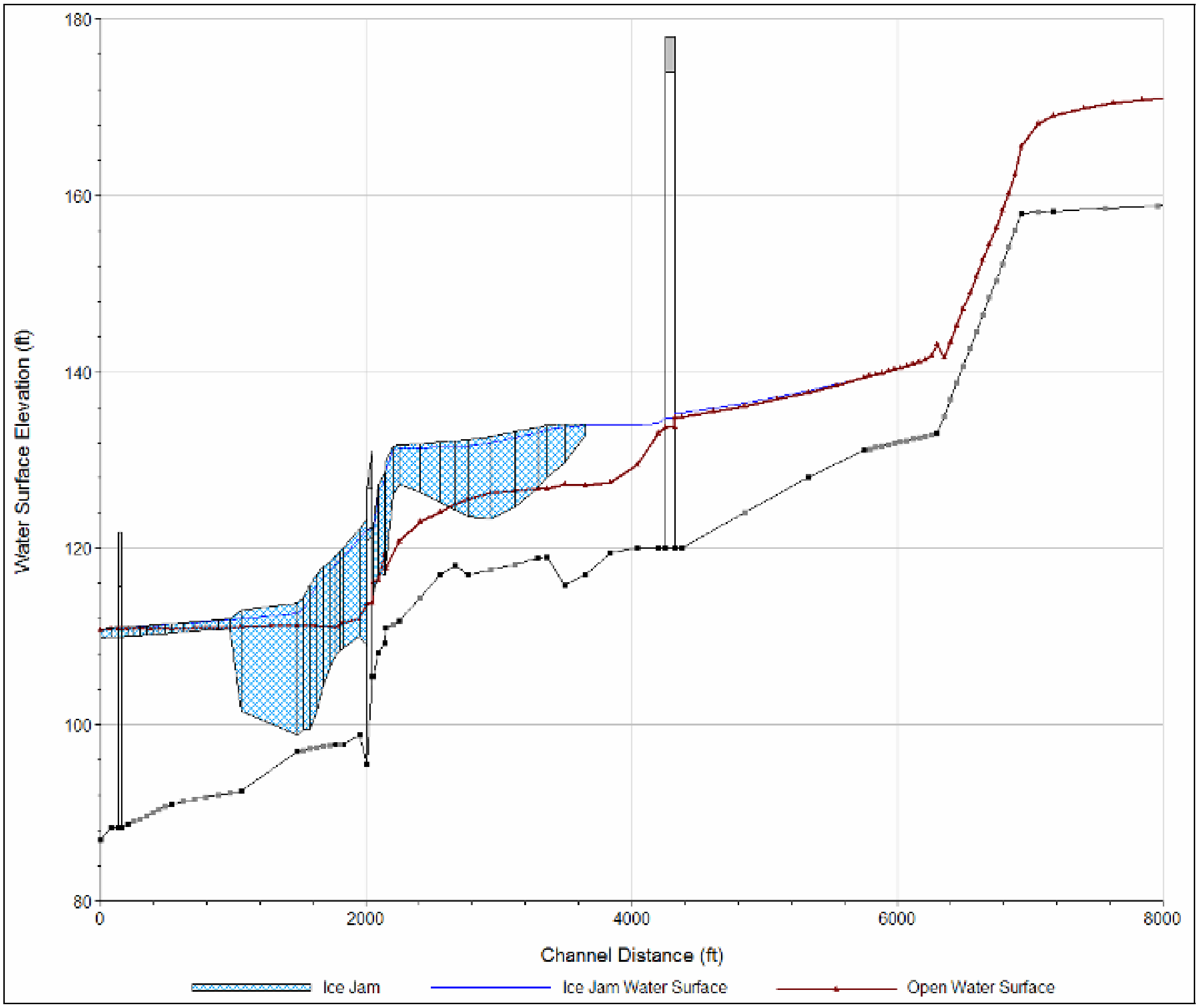

Figure 11. HEC-RAS ice jam and open water profiles, with dam removed for the ten-year discharge.

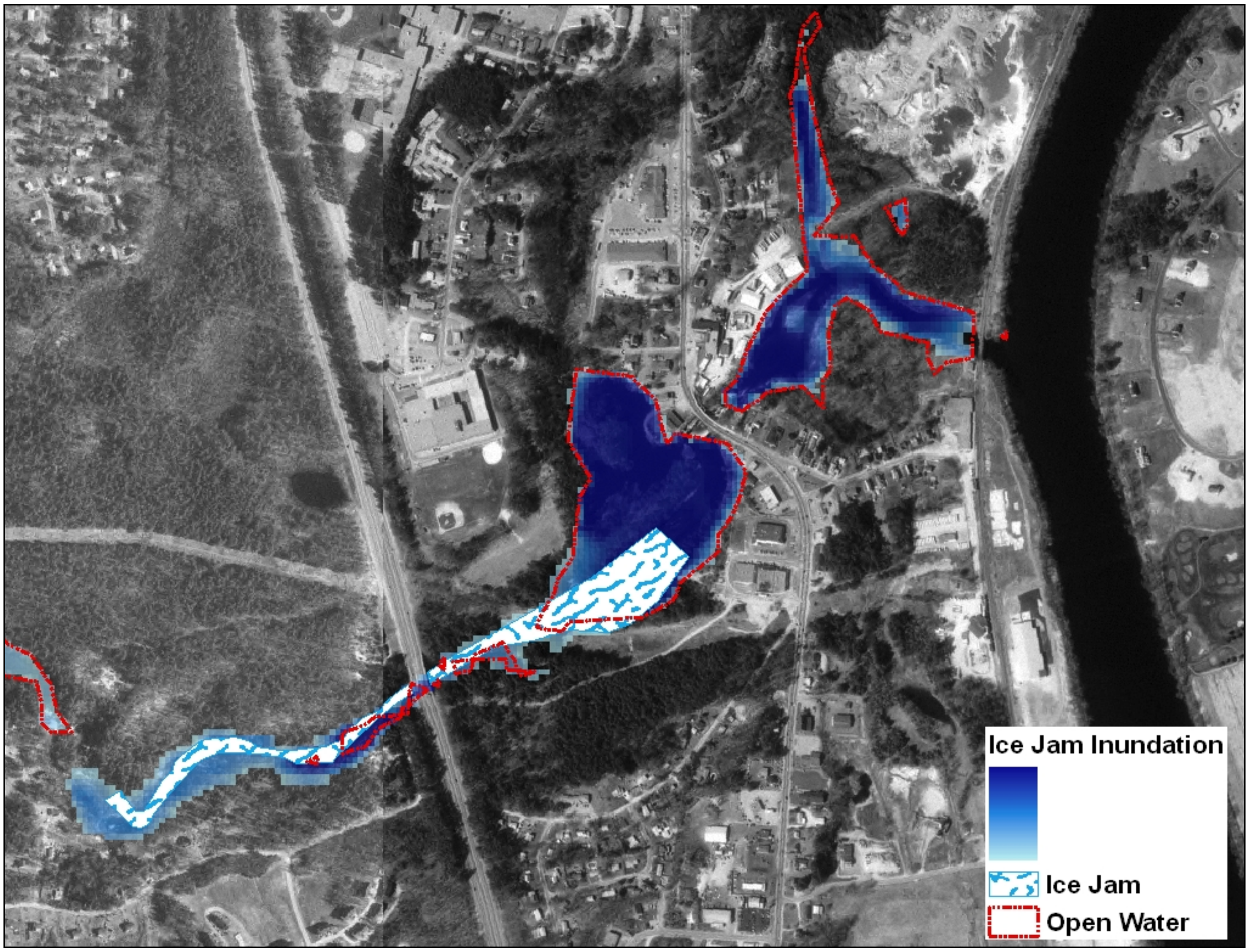

Figure 12. Estimate of ice jam locations and inundated areas with dam in place for the two-year discharge.

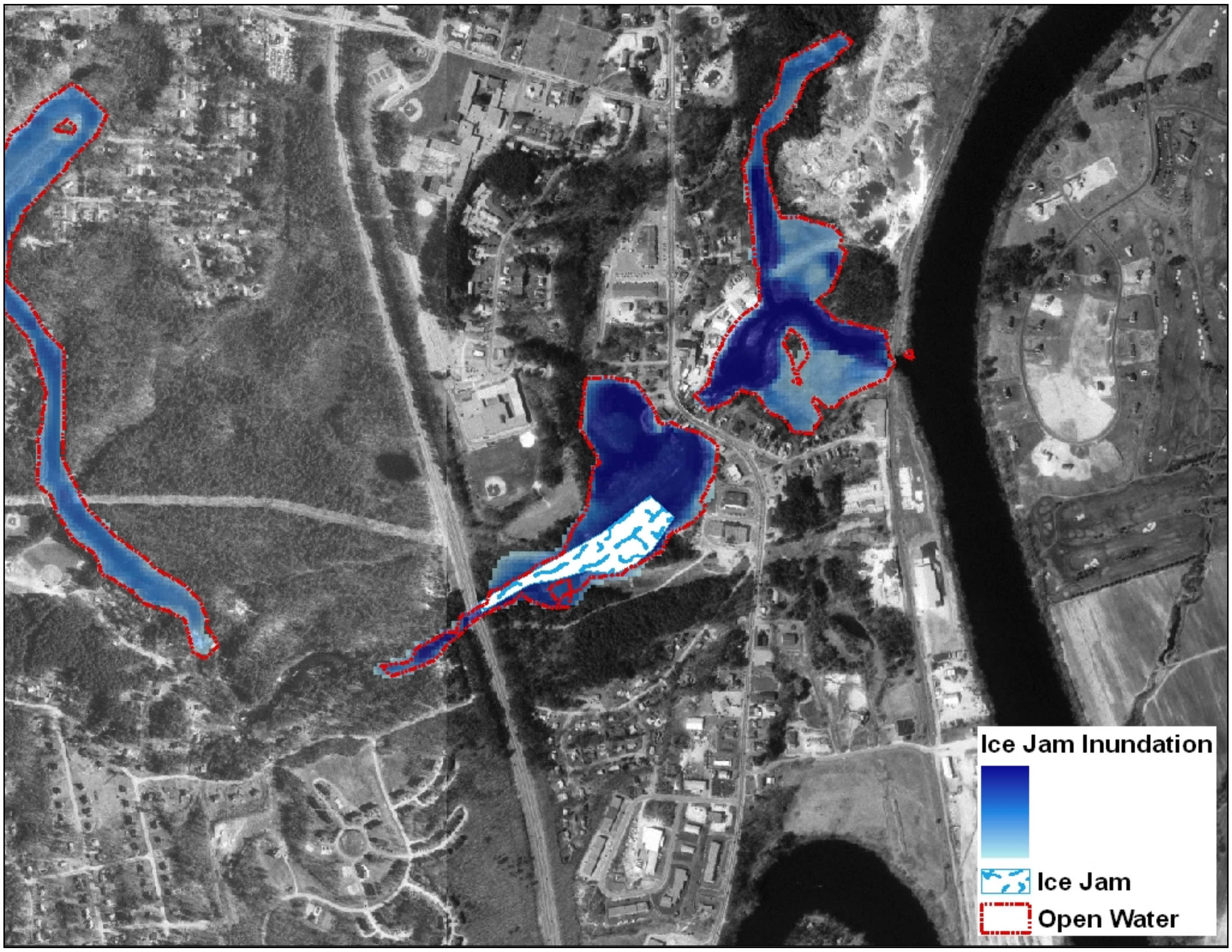

Figure 13. Estimate of ice jam locations and inundated areas with dam in place for the ten-year discharge.

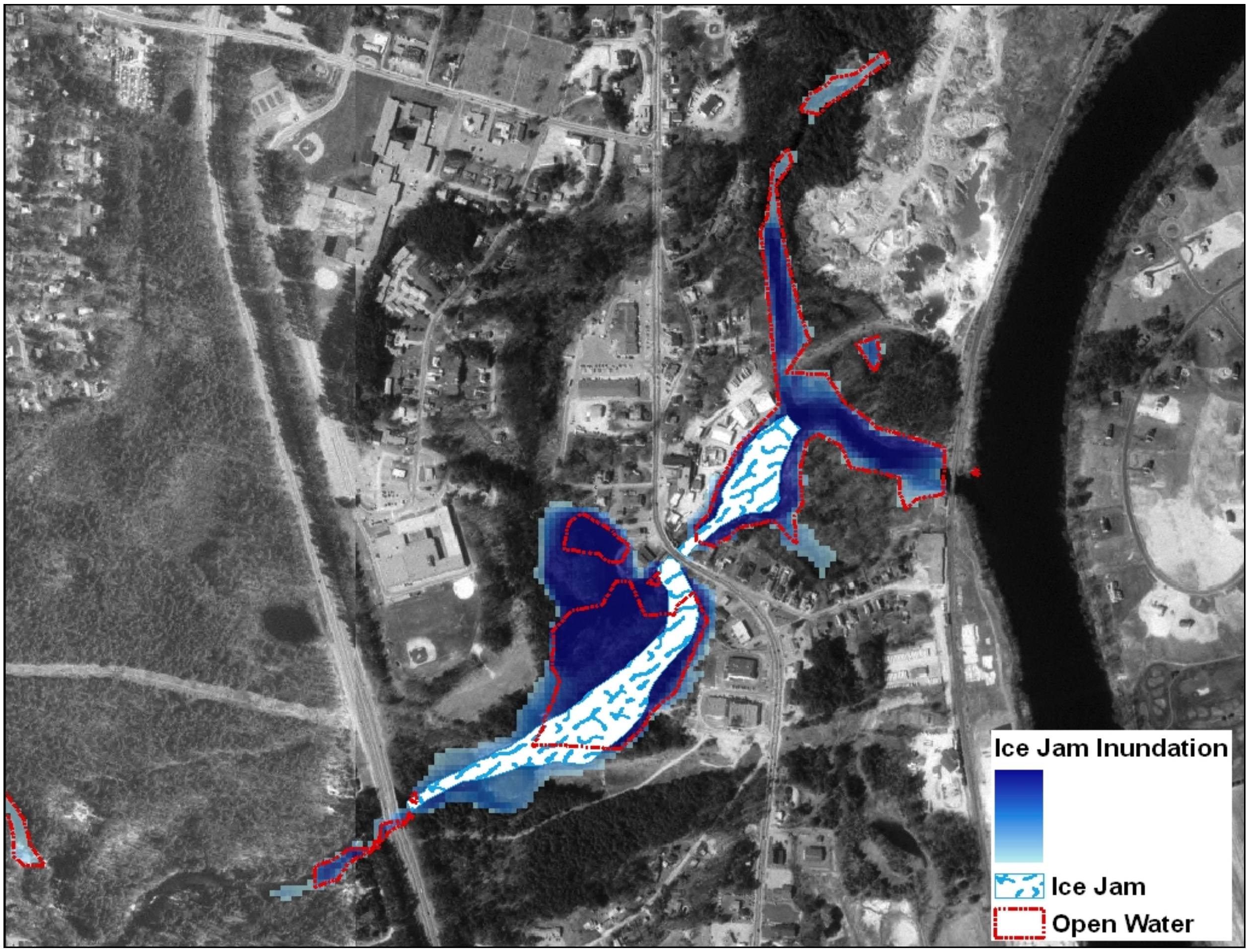

Figure 14. Estimate of ice jam locations and inundated areas with dam removed for the two-year discharge.

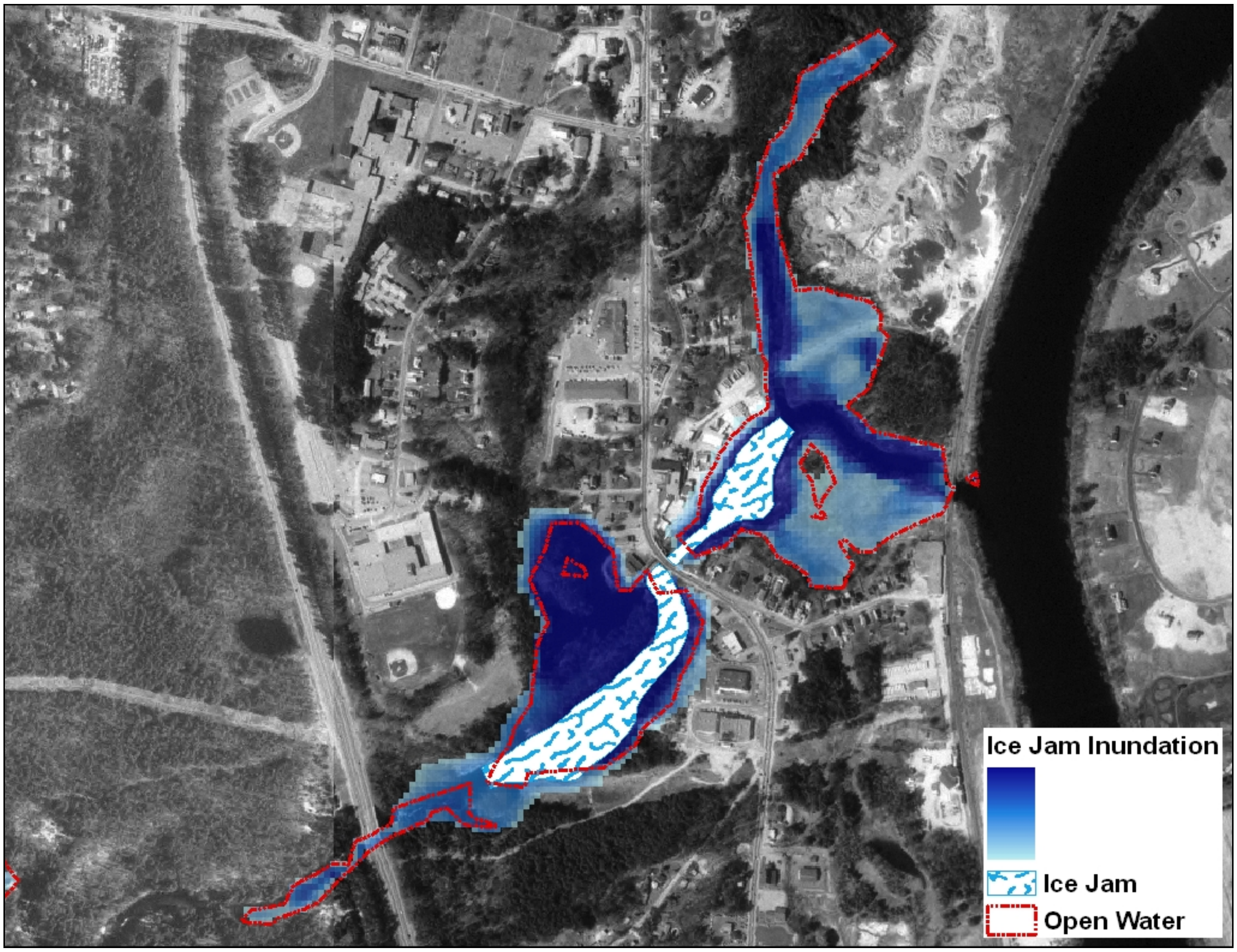

Figure 15. Estimate of ice jam locations and inundated areas with dam removed for the ten-year discharge.

7 Ice Impacts Resulting from Merrimack Village Dam Removal

Based on this analysis, it is estimated that breakup ice runs that currently stop behind the impoundment of the Merrimack Village Dam will travel farther downstream and stop in the backwater of the Merrimack River. Ice jams occurring downstream have the potential to extend upstream through the Chamberlain Bridge, resulting in higher water surface elevations than during similar open water events. Of particular concern is the impact of ice to the historical Chamberlain Bridge. Figure 16 describes the terms used in this report to refer to sections of the Chamberlain Bridge.

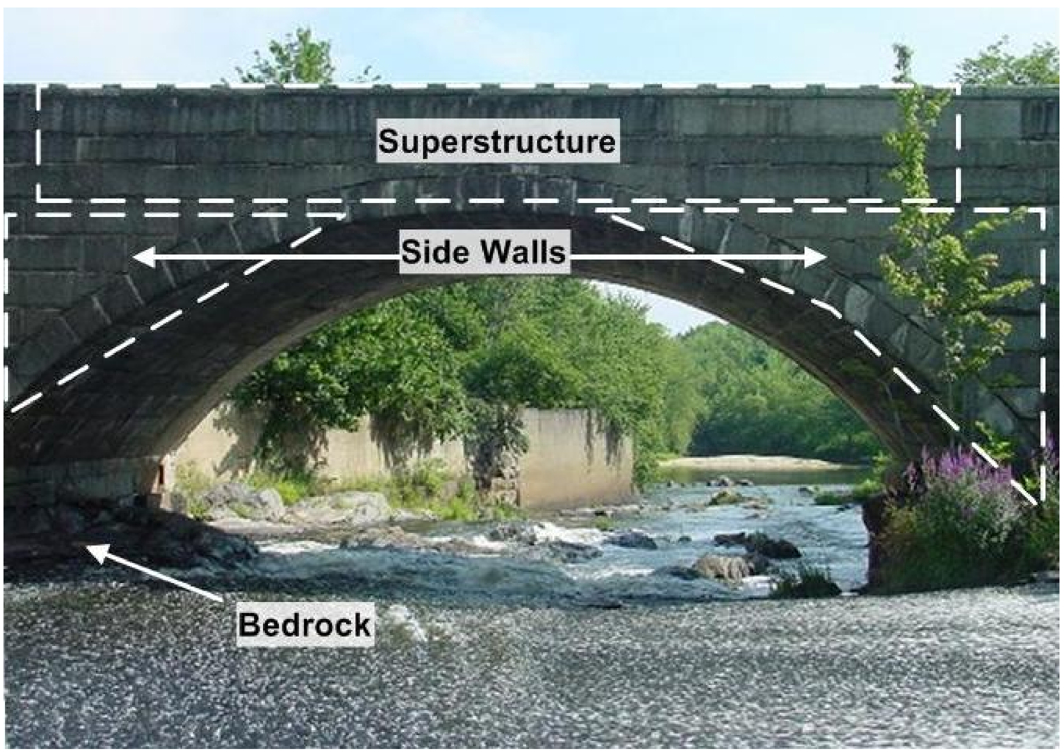

Figure 16. Chamberlain Bridge, looking downstream.

Generally, crushing ice loads acting on the bridge superstructure in the downstream direction provide the greatest risk to the bridge safety. Beltaos et al. (2007) noted that a bridge superstructure is particularly vulnerable to ice loads because of the relatively large area of impact compared to typical bridge piers. The suggested solution is to ensure the water and ice stage levels do not reach the superstructure during bridge design. Ice jams

modeled on the Souhegan River downstream of the bridge extended upstream through the bridge in both the two-year and the ten-year discharge simulations. In each case, the ice was approximately 4–5 ft below the bridge superstructure. The underside of the Chamberlain Bridge forms an arch that extends between banks. The ice jam extending through the bridge may impact the lower side walls of this arch. Forces acting on the vertical side walls are a result of ice jams and the movement of ice rubble, which tend to be significantly smaller forces than ice crushing forces. Ice forces are expected to act over a height of 12 feet on the face of the side walls and were calculated according to AASHTO (2007), assuming an ice pressure of 0.2 KSF. The estimated ice force acting on the side walls during an ice jam event is 24 Kips.

Another concern at bridges is under-ice scour that might destabilize the bridge piers and abutments. The constricted flow area due to the ice cover can result in higher velocities, increased turbulence, and scour of erodible bed material (Zabilansky et al. 2006). Through the Chamberlain Bridge, the slope steepens and velocities greater than 10 ft/s can be seen during open water flow. However, scour does not appear to be a significant issue at the Chamberlain Bridge, as the bridge is built upon exposed bedrock (Gomez and Sullivan 2004).

With the dam removed, the two-year discharge ice-affected water surface profile was higher through the bridge, and the ice jam extended upstream almost to the F.E. Everett Turnpike Bridge. The ten-year discharge ice jam simulation with the dam removed looked very similar to the two-year simulation. In the ten-year discharge simulation, the water was forced out of bank on the right, downstream of the bridge. This would effectively release pressure on the jam and validates the assumption that the most significant ice jam event would occur between the two-year and ten-year discharge. Based on the flood inundation mapping, it does not appear that ice jams farther downstream will result in significantly higher water surface elevations than during similar open water events. For that reason, increased flooding due to ice jams once the dam is removed does not appear to be a significant issue.

8 Summary and Conclusions

Dam decommissioning and removals are increasingly frequent in the United States for purposes of stream rehabilitation, recreation, and economics. The potential for increased frequency and severity of ice jams resulting from a dam removal on a northern river needs to be investigated during the evaluation phase of a dam decommissioning.

This study investigated the impacts of the Merrimack Village Dam removal on the formation of potentially damaging ice jams in the Souhegan River. In order to achieve that objective, the following steps were taken:

- Historical ice jam reports and river geomorphology were analyzed to determine the most likely location for ice jams to occur once the dam is removed. Historical ice jam information was found at the CRREL Ice Jam Database Web site: https://rsgis.crrel.usace.army.mil/icejam/.

- Historical meteorological (NWS) and hydrological (USGS) data were used to estimate ice thickness, ice jam volume, and a range of likely discharges during an ice jam event.

- A HEC-RAS hydraulic model of the Souhegan River was geo-referenced and used to estimate the ice jam thickness and resulting water surface profiles with and without an ice jam in place for both the pre- and post-dam-removal conditions. Several iterations were necessary to match the ice volume conditions at each discharge.

- The geo-referenced results were imported into GIS to compare the ice jam flood inundation with and without the dam in place.

Based on this analysis the following conclusions were made:

- The most likely location for a breakup ice run to jam once the dam is removed is where it meets the backwater of the Merrimack River, approximately 1,000 feet upstream from the mouth of the Souhegan River at the location of a large sediment island. This analysis assumes that ice currently stopped behind the Merrimack Village

Dam impoundment will be able to pass farther downstream once the dam is removed.

- An ice jam at this location will extend upstream through the Chamberlain Bridge, resulting in a higher water and ice surface level through the bridge than during an open water event at the same discharge. The ice and water surface levels are not expected to contact the top portion of the bridge or the roadway.

- The ice jam extending through the bridge may impact the vertical side walls of the bridge. Forces acting on the vertical side walls are a result of the movement of ice rubble and tend to be significantly smaller forces than ice crushing forces. The estimated ice force acting on the side walls during an ice jam event is 24 Kips.

- Although scour of erodible bed sediment during ice jams at bridges is often a concern due to the destabilization of bridge piers and abutments, scour does not appear to be an issue at the Chamberlain Bridge, as the bridge was constructed on exposed bedrock.

- Based on the flood inundation mapping, it does not appear that ice jams farther downstream will result in significantly higher water surface elevations in developed areas than during similar open water events. For that reason, increased flooding due to ice jams once the dam is removed does not appear to be a significant issue.

Performing an ice impact study can save money and time and reduce the likelihood of adverse impacts if performed prior to removing the dam. This case study demonstrates the steps required to make an informed decision regarding the impacts of dam removal on the ice jam regime.

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14. ABSTRACT

Many dams across the United States are being decommissioned as a result of structural deficiencies or a desire to restore fish passage and to restore the natural stream. On northern rivers, dam removal affects the river ice processes and can result in increased ice jams and ice jam-related flooding. An analysis of the river system prior to dam removal is often necessary to ensure that increased ice jams, flooding, and damages do not result. This case study presents the types of analyses needed to investigate the ice impacts of the potential removal of the Merrimack Village Dam on the Souhegan River in Merrimack, New Hampshire. Of particular interest were the potential impacts to the historic Chamberlain Bridge. A HEC-RAS hydraulic model was used to estimate the ice jam thickness and resulting water surface profiles with and without an ice jam in place for both the pre- and post-dam-removal conditions. The results of this analysis indicate that removing the Merrimack Village Dam will not pose significant risk to the Chamberlain Bridge or to the area downstream.

15. SUBJECT TERMS

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